

Microfabrication of Linear Translator Tuning Elements in Submillimeter-Wave Integrated Circuits

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Abstract—A micromechanical planar tuning element has been developed and demonstrated in a fully monolithic 620-GHz integrated circuit. It allows for the mechanical variation of the electrical length of a coplanar transmission line tuner and is called a *sliding planar backshort* (SPB). It consists of a movable patterned rectangular metal plate confined by polyimide flanges along two of its edges to allow guided linear translation along the length of a dielectric-coated coplanar transmission line. Its fabrication involves an application of sacrificial-layer and molding techniques to materials and processes which are compatible with the fabrication of a wide range of submillimeter-wave integrated circuits. This is the first reported micromechanically adjustable tuning element demonstrated at submillimeter wavelengths. [319]

Index Terms—Backshort, coplanar, MEMS, micromachining, millimeter wave, monolithic integrated circuit, planar tuning element, submillimeter wave.

I. INTRODUCTION

MICROMACHINING techniques offer great potential to millimeter- and submillimeter-wave circuit technology. Critical dimensions in these circuits decrease with increasing operating frequency, creating fabrication difficulties which can be addressed through micromachining. Additionally, micromachining techniques and micromechanical components can allow for the development of new unconventional high-frequency circuitry which can offer superior performance.

Silicon *bulk micromachining* techniques have already been demonstrated in submillimeter- and near-submillimeter-wave circuits. Reflecting cavities for membrane-supported planar submillimeter-wave antennas have been fabricated by stacking anisotropically etched silicon wafers [1]. A similar selective etching technique has also been employed to create waveguide sections in silicon, incorporating internally suspended membranes which can allow for the integration of planar high-frequency devices [2]. Bulk techniques have also been

used to selectively remove substrate material from critical regions in planar high-frequency transmission line components in order to reduce losses and enhance isolation [3]. Silicon *surface micromachining* techniques offer potential in this field as well, as they have been used to create various submillimeter-scale rotating and translating structures [4] on which mechanically adjustable submillimeter-wave components can be based. Techniques similar to those demonstrated in simplified LIGA-like processes [5] can potentially make surface micromachining techniques practical in a variety of conventional high-frequency circuits.

At millimeter and submillimeter wavelengths, the performance of common semiconducting and superconducting devices is severely degraded by the effects of parasitic reactances inherent in their geometries [6], [7]. These effects are not easily characterized, and adjustable impedance matching circuits are typically needed to make practical use of such devices. A common approach is to embed the device in a waveguide circuit and employ mechanically adjustable waveguide backshorts as tuning elements which serve to optimize the device performance by compensating for the parasitic reactance [8]. The critical dimensions for these circuits are very small, decreasing in size as the frequency of interest increases. This makes fabrication of such waveguide circuits exceedingly costly and difficult and has motivated interest in alternative planar approaches.

Monolithic integrated-circuit technology promises a practical means for realizing reliable and reproducible planar millimeter- and submillimeter-wave circuits. Planar circuits are fabricated through photolithographic techniques, which allow for the cost-effective production of intricate designs not possible with waveguide technology. These circuits, however, must also provide compensation for parasitic device reactances. Conventional planar technology allows for only fixed tuning elements, providing no means for postfabrication optimization of performance [9]. This makes characterization of the component elements critical, and it is not usually possible to achieve satisfactory results without multiple design and fabrication iterations. It would be desirable to incorporate in these planar circuits the same kind of mechanically adjustable tuning available in waveguide circuits.

An adjustable planar tuning element, which functions in a planar circuit analogously to a backshort in a waveguide circuit, has been developed along with a process for its fabrication as an integral part of a millimeter- or submillimeter-wave monolithic circuit. This is the first reported demonstration of an integrated micromechanically adjustable tuning element

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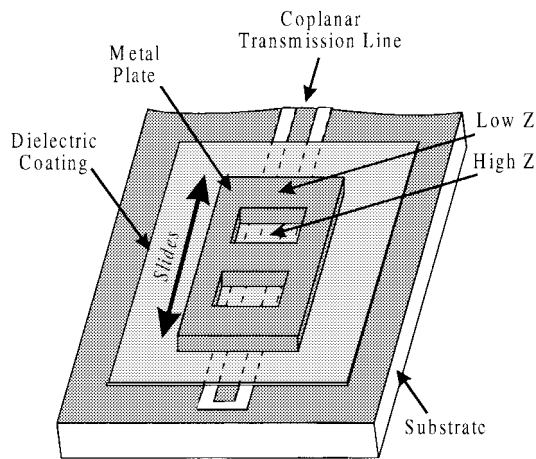


Fig. 1. Conceptual illustration of an SPB tuning element. A patterned metal plate slides over a dielectric-coated planar transmission line to vary the electrical length.

at submillimeter wavelengths. The tuning element, called a *sliding planar backshort* (SPB), is formed as an integral part of a coplanar transmission line tuning stub, using only conventional micron-scale fabrication techniques commonly employed for submillimeter-wave circuits, which include UV lithography, evaporated and electroplated metals, and sputtered and spun-on dielectrics. The SPB can be used in developmental integrated circuits as an aid for device characterization or as a means to optimize in-use performance for a variety of submillimeter-wave integrated circuits.

II. INTEGRATED SPB's

An SPB consists of a rectangular metal plate, with appropriately sized and spaced holes, which rests on top of a dielectric-coated planar transmission line, as shown in Fig. 1. The impedance of the sections of line covered by metal is greatly reduced, while the uncovered sections retain their higher impedance. Each of these sections is approximately one quarter of a wavelength long, and the cascade of alternating low- and high-impedance sections results in an extremely low-impedance termination. This termination can be moved to vary the electrical length of a planar transmission line tuning stub by simply sliding the metal plate along the length of the line. Such adjustable tuning stubs can be used in a variety of ways to adjust the impedance match between the various elements of a circuit [10]. The semiempirical design of the SPB was originally carried out with a 2-GHz-scale model [11], and SPB tuners have since been successfully demonstrated as discrete components at frequencies up to 100 GHz [12].

The wavelength for a signal guided on a planar transmission line is determined by the frequency of the signal and the dielectric properties of the substrate, decreasing in size with increasing frequency and dielectric constant [13]. Since an SPB tuner works as a distributed transmission line component, its dimensions vary accordingly. At low frequencies, these dimensions are large by micromachining standards, even for substrate materials with relatively high-dielectric constants like silicon. At frequencies above 100 GHz, however, the dimensions can be on the order of hundreds or tens of microns.

At 620 GHz, an SPB on a silicon dioxide substrate can be about 200 μm wide, comparable in size to linear translating structures fabricated through the surface micromachining of silicon [4]. Unfortunately, the processes and materials typically used for such structures can be inappropriate for, or incompatible with, those often needed in submillimeter-wave circuit fabrication.

Micromachining with polysilicon components and silicon dioxide sacrificial layers typically requires high-temperature chemical vapor deposition (CVD) or furnace growth and aggressive and hazardous chemical etchants. Many conventional submillimeter-wave circuits, containing delicate thin-film structures, diodes, and other devices, cannot easily accommodate such processes. It is desirable that the sliding element of an SPB tuner be made from a good conductor through a process which involves temperatures and reactions which can be safely used on a wide range of insulating substrates which already contain thin-film circuitry. Fortunately, key features from the silicon-based technique can be suitably combined with an LIGA-like UV process to allow for the fabrication of SPB tuners in a variety of submillimeter-wave circuit applications, using only rudimentary fabrication facilities and very low-hazard materials and processes [14].

An all-monolithic quasi-optical 620-GHz direct-detection circuit was developed to demonstrate the operation of integrated submillimeter-wave SPB tuners. This circuit uses a dielectric-filled parabola [15] substrate lens to focus radiation onto a slot antenna and couples this radiation to a detector by means of two coplanar waveguide (CPW) transmission lines, each with integrated SPB tuners. One SPB tuner creates a variable reactance in series between the antenna and the detector, potentially serving to compensate for any unwanted reactance when the slot is not resonant. The other SPB tuner creates a variable susceptance in parallel with the detector and could be used to compensate for the parasitic capacitance found in some otherwise desirable submillimeter-wave devices. The entire circuit can be fabricated through simple processes commonly employed in the making of millimeter- and submillimeter-wave integrated circuits.

III. SUBMILLIMETER-WAVE CIRCUIT FABRICATION

Submillimeter-wave circuits are made with a variety of low-loss dielectric substrates, high-speed semiconductor devices, and even superconducting thin films. The choices depend on the applications, and components which are not restricted to one medium or process are desirable.

Except for the SPB tuners, the 620-GHz detector circuit used here is conventional; it incorporates materials, components, and fabrication processes common to many fixed-tuned submillimeter-wave circuits. Fused quartz was used for the substrate lens, which provides low-loss transmission line properties and a reasonable match to free space. The transmission line and antenna circuitry were straightforward thin-film patterns, and a patterned thin film of bismuth was used as a thermoelectric detector [16]. While this type of detector does not provide the sensitivity of semiconducting and superconducting mixing elements, it offers the advan-

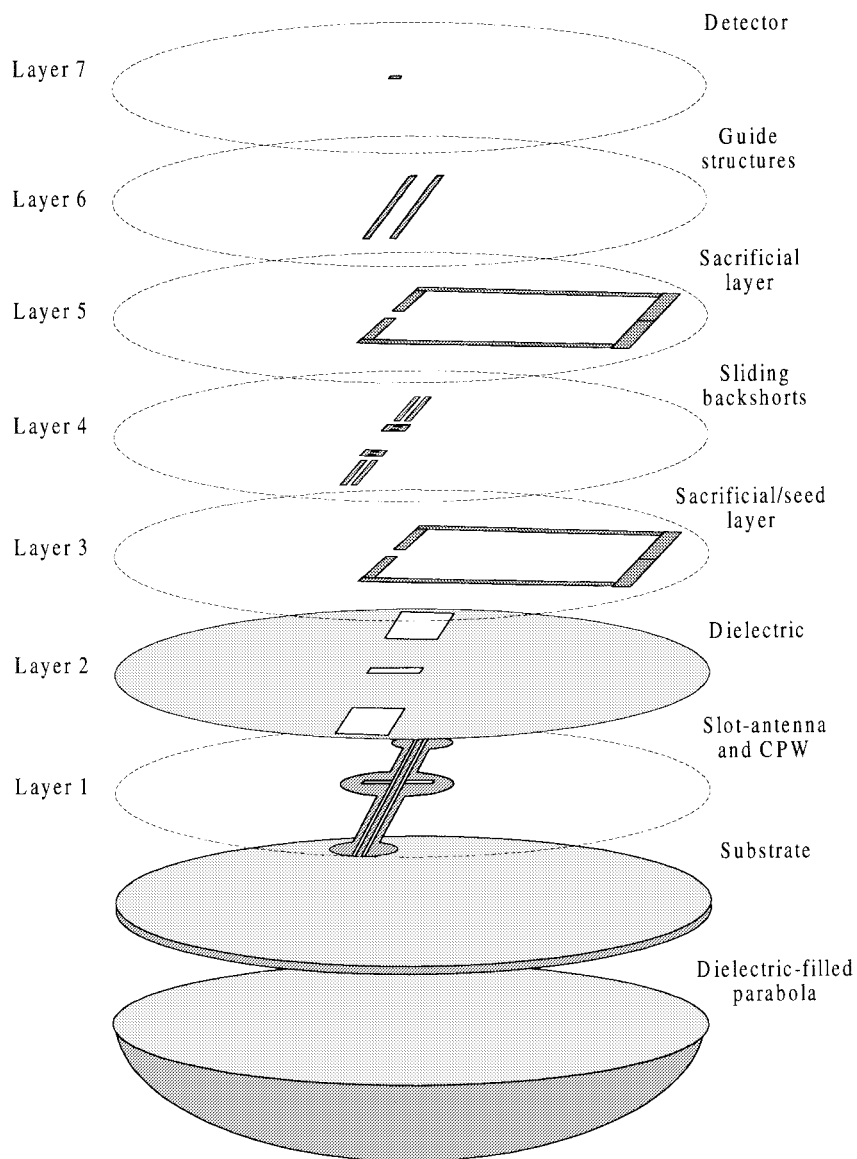


Fig. 2. Exploded illustration of the seven-layer circuit. Two SPB tuners were included using conventional submillimeter-wave circuit fabrication techniques.

tage of working at room temperature, with only a single layer of processing. Techniques are available, however, for integrating gallium arsenide Schottky diodes, superconductor-insulator-superconductor (SIS) junctions, and similar devices in this circuit [17], [18]. The completed circuit required seven masks and seven processing layers, and the process is illustrated in Fig. 2.

The entire circuit was fabricated at the center of a round 254- μm -thick 19-mm-diameter fused-quartz wafer which could be seamlessly installed on a quartz lens. The first process layer consisted of 1000 Å of gold, with 70- μm chrome adhesion layers above and below, deposited by electron-beam evaporation and etched to form the slots for the antenna and CPW transmission lines. Since the 620-GHz signal must pass through the circuit in order to utilize the substrate lens, excess metal was also etched, leaving only enough in the vicinity of the transmission lines and antenna to serve as a proper ground plane. A 1000-Å layer of silicon dioxide was then applied to provide mechanical and dc isolation between the CPW lines

and subsequent layers. The silicon dioxide was deposited on the circuit by low-temperature radio frequency (RF) sputtering using a photoresist lift-off stencil to define small openings which would allow the thin-film detector and bias wire bonds to make ohmic contact to the CPW lines beneath it. Two SPB tuning elements were then added by the process described in the following section. The final processing layer consisted of a thermally evaporated 6000-Å-thick bismuth film patterned with a photoresist lift-off stencil.

IV. SPB TUNER FABRICATION

The procedure used for fabricating the micromechanical SPB tuners on the dielectric-coated CPW lines is illustrated in Fig. 3. The processing steps are not so different from those for capacitors and air bridges in fixed tuned circuits, but produce a more versatile tuning element. Thus, it was possible for this entire circuit to be fabricated with low-hazard processes common to high-frequency circuit fabrication without the use of an environmentally controlled clean room [19], [20].

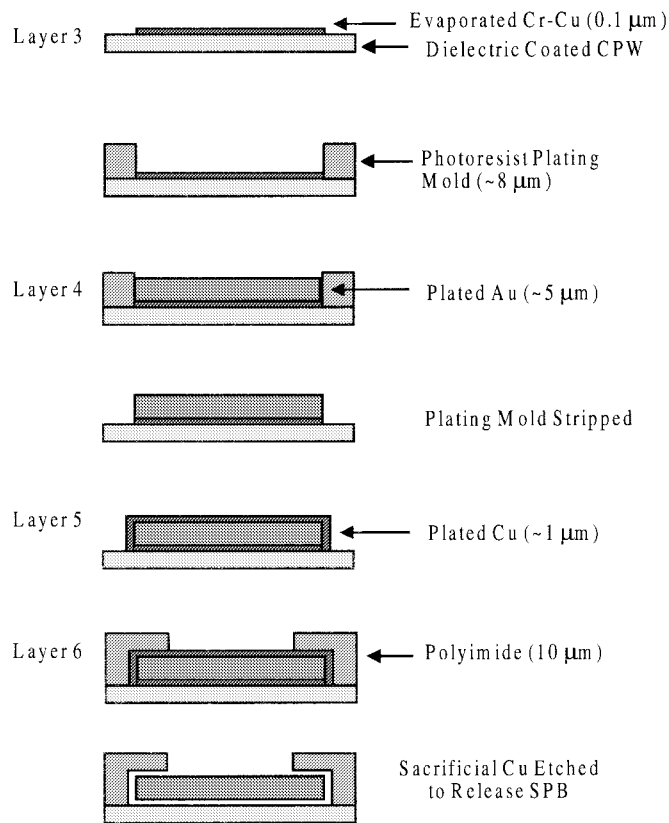


Fig. 3. Simplified illustration of the SPB fabrication process. Sacrificial layers are used to form an SPB which is constrained by polyimide guide structures.

A photoresist lift-off stencil was applied and patterned to define a sacrificial-seed layer. This pattern consisted of rectangular strips over each CPW line, each as wide as the SPB ($200\ \mu\text{m}$) and extending to the edge of the substrate to allow for electrode connection. This third layer was formed by depositing a $1700\text{-}\text{\AA}$ layer of copper over a $70\text{-}\text{\AA}$ chrome adhesion layer through electron-beam evaporation and then lifting the stencil and unwanted film in acetone.

Next, an $8\text{-}\mu\text{m}$ layer of photoresist was applied to the circuit, patterned to form a mold layer, and hard baked. This layer defined the shape of each SPB, several sacrificial pieces used to define the region into which each SPB would slide, and two one-square-mm patches. These patterns were all formed over the sacrificial-seed layer to allow for electroplating, with the large square patches serving to increase the plating area and allow for the use of an easily maintained dc plating current. The wafer was then dipped in gold electroplating solution where $5\text{-}\mu\text{m}$ -thick patterned gold structures were plated within the mold, forming the fourth circuit layer.

The mold layer was then striped in N-methyl 2-pyrrolidone, and a $1\text{-}\mu\text{m}$ sacrificial copper coating was applied to the exposed SPB and sacrificial structures by connecting the circuit to an electrode and immersing it in copper electroplating solution. This formed the fifth circuit layer. A $13\text{-}\mu\text{m}$ -thick layer of photosensitive polyimide precursor was then spun onto the circuit and UV patterned to form two digitated strips, each overlapping a side of the copper-coated gold structures. The

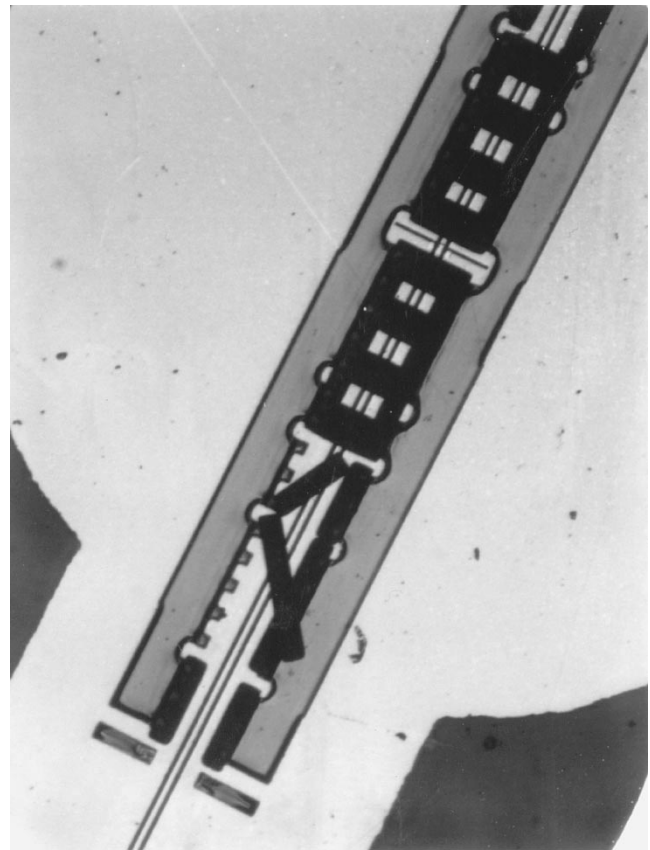
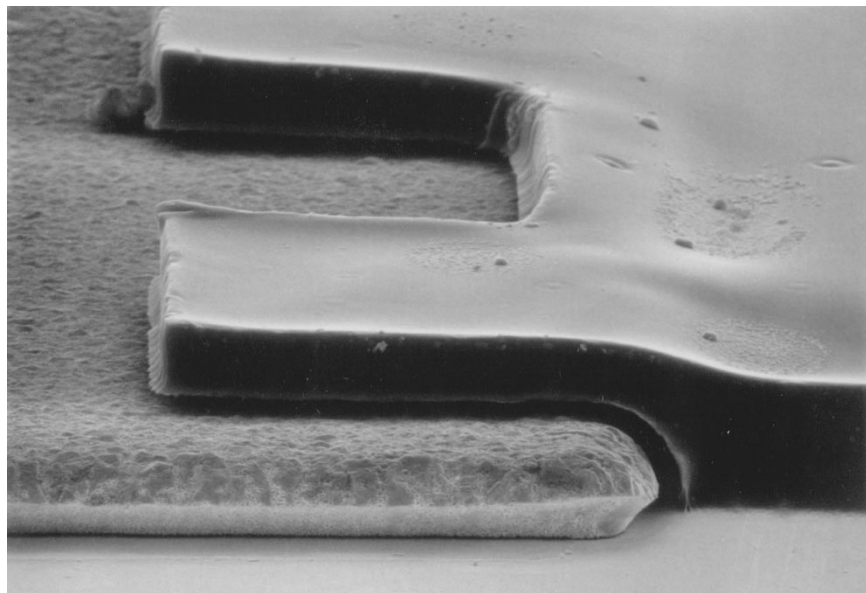


Fig. 4. Microscope photograph showing the removal of two of the sacrificial gold structures (angled bars) used to form the polyimide guides. Once these have all been removed, the SPB tuners can slide freely along the transmission line within the confines of the guides.

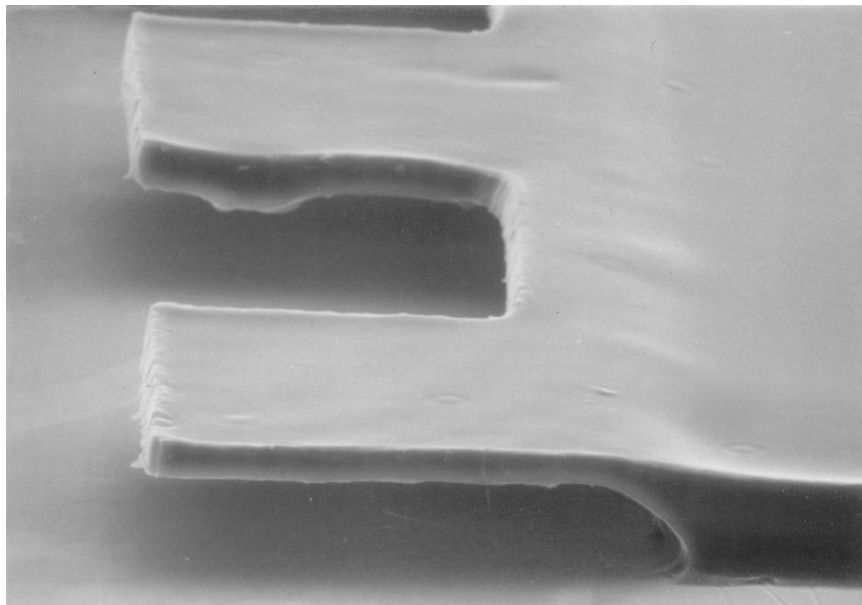
strips were then cured in an inert gas environment to form $9\text{-}\mu\text{m}$ -thick polyimide guide structures.

Finally, the copper plating and sacrificial-seed layers were removed through wet etching to release the gold SPB and sacrificial structures. The sacrificial pieces shown in Fig. 4 were then removed from under the polyimide guides to allow the SPB structures to slide within the guides along the surface of the CPW lines. The digitated structure of the guides both minimized the chance of binding between the SPB and its guide and provided reference marks for positioning the tuners. Fig. 5(a) and (b) shows a scanning electron microscope (SEM) photograph of a guide structure with its confined SPB in view and one of a guide structure with its SPB removed, respectively. Fig. 6 shows a released SPB tuner in its entirety.

The fabrication of state-of-the-art submillimeter-wave integrated circuits typically requires constant painstaking attention, which is justified by the fact that a single functioning circuit can yield a great deal of valuable data. The circuit demonstrated here required a full wafer and seven processing layers and was no exception. Fabrication, however, was successfully carried out with very limited processing equipment and in facilities with little or no environmental regulation. While yield was not optimized or specifically evaluated, a developmental wafer processed with an array of ten test tuners yielded six elements, which could slide smoothly without sticking, and four damaged elements. Similarly, of the final six circuit wafers simultaneously processed to produce one suitable for



(a)



(b)

Fig. 5. Close-up SEM photograph of one side of an SPB tuner. (a) A polyimide guide structure is shown with a 5- μm -thick SPB beneath it and (b) another with the SPB removed.

submillimeter-wave measurements, two exhibited tuner binding—one due to nonuniform gold plating and the other due to incomplete coverage of the electroplated sacrificial copper. The yield for producing a functioning submillimeter-wave bismuth detector in such a circuit is typically lower than that of these tuners.

V. TUNER FUNCTION

The processed wafer was mounted over a substrate lens to allow quasi-optical coupling to a 620-GHz backward wave oscillator source. The performance of the integrated SPB tuners was demonstrated by using them to vary the power delivered from the slot antenna to the bismuth detector by altering the impedance match between them. The delivered power was

measured using a lock-in amplifier, and a theoretical model was also derived to calculate the circuit behavior in order to predict and verify the measured performance [20].

The tuners were positioned manually using a probe with an ox-hair tip which provided adequate manipulation control for the 620-GHz experiment. Ox hair was determined to be well suited for the application as it had sufficient stiffness for pushing the tuner, yet could safely brush against the polyimide and silicon dioxide surfaces without causing damage. Power measurements were made for various alignments of the tuners at 20- μm increments, which is one sixteenth of a guided wavelength. The circuit was designed to accommodate movement of the tuners over three guided wavelengths, though in a practical circuit there would be no need for positioning

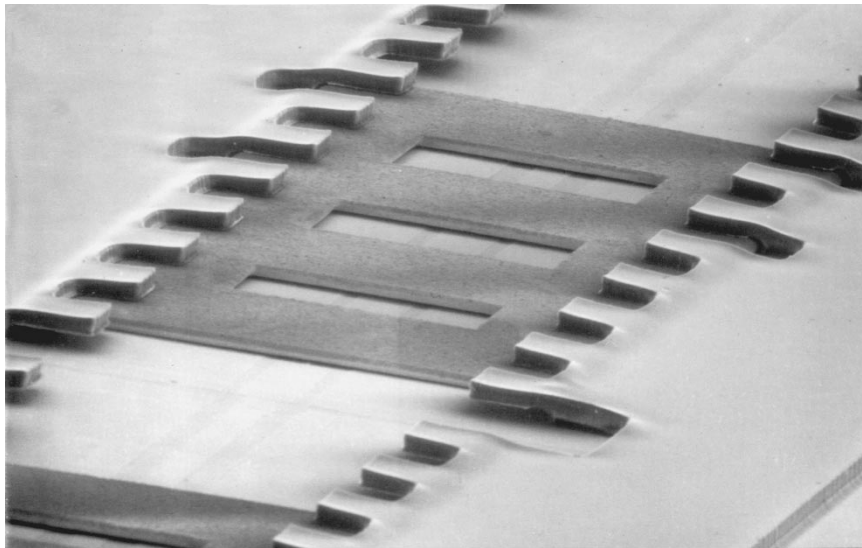


Fig. 6. SEM photograph of an integrated SPB tuner. An ox-hair probe was used to push each 200- μm -wide SPB along its guide to vary the electrical length of the CPW line beneath it.

the tuner beyond the first one-half guided wavelength as the performance pattern repeats after this, only with greater loss due to the added length of the transmission line. While over most of the range the tuners exhibited no sticking, positioning by successive 20- μm increments was difficult and so the measurements were made for a more or less random order of tuner positions. The polyimide guides and stopping structures kept the tuners within the desired range at all times, and optimum circuit performance could be repeated without much difficulty. The submillimeter-wave circuit response was successfully varied over a 15-dB range, which demonstrated adequate tuning capability for providing a good impedance match between a wide range of typical submillimeter-wave devices with high-parasitic reactances, such as SIS devices and Schottky diodes, and resonant planar antennas, including slots, dipoles, and self-complementary structures. Measured results for independent position sweeps for each SPB tuner agreed very closely with theory and could be accurately repeated in tests conducted over a two-week period. The submillimeter-wave function and performance of this circuit is described in more detail elsewhere [21], [22].

The fabrication techniques used for the tuner and all-planar circuitry are well suited to scaling the design to frequencies up to several terahertz. More precise positioning control may be necessary in such circuits and could be achieved through the use of mechanical manipulators such as those used for positioning optical fibers or through electrostatic [23], shape-memory alloy [24], or other integrated actuator techniques. The sliding structure also has the potential to be used for other micromechanical millimeter- and submillimeter-wave circuit components such as switches, adjustable antenna elements, and aperture shutters.

VI. CONCLUSION

A new submillimeter-wave tuning element has been developed along with a technique for its fabrication as an integral part of a monolithic circuit. The technique is based on silicon

surface micromachining and LIGA, but incorporates only processes and materials suitable for common submillimeter-wave integrated circuits. The performance of these tuning elements has been demonstrated at 620 GHz through mechanical manipulation. This is the first reported demonstration of micromechanically adjustable tuning in a submillimeter-wave integrated circuit. Potentially, the sliding element can be adapted to serve additional millimeter- and submillimeter-wave circuit functions at frequencies up to several terahertz and, if necessary, could be made to self-actuate through the application of electrostatic, shape-memory alloy, or other microelectromechanical actuation techniques, with appropriate consideration made for individual circuit compatibility with thermal, electrostatic, and other environmental factors.

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